# Simulation-based scanner tuning using FlexRay Capability and Scatterometry

Karsten Bubke[1], Matthias Ruhm[2], Rafael Aldana[3], Martin Niehoff[3], Xu Xie[3], Justin Ghan[3], Paul van Adrichem[2], Holger Bald[1], Paul Luehrmann[2], Stefan Roling[1], Rolf Seltmann[1]

[1]GlobalFoundries, Wilschdorfer Landstrasse 101, D-01109 Dresden, Germany
[2]ASML – Veldhoven, The Netherlands
[3] BRION Technologies, an ASML company – Santa Clara CA, United Staates

## ABSTRACT

Differences in imaging behaviour between lithographic systems of the same wavelength result in variations of optical proximity effects (OPE). A way to compensate these irregularities is through scanner tuning. In scanner tuning, scanner specific adjustments are obtained through the determination of scanner knob sensitivities of relevant structures followed by an optimization to adjust the structure CD values to be close to the desired values.

Traditionally, scanner tuning methods have relied heavily on wafer-based CD metrology to characterize both the initial mismatch as well as the sensitivities of CDs to the scanner tuning knobs. These methods have proven very successful in reducing the mismatch, but their deployment in manufacturing has been hampered by the metrology effort. In this paper, we explore the possibility of using ASML's LithoTuner PatternMatcher FullChip (PMFC) computational lithography tool to reduce the dependence on wafer CD metrology.

One tuning application using flexray illumination instead of traditional scanner knobs is presented in this work; in this application individual critical features in wafer printing are improved without affecting other sites. The limited impact of tuning on other structures is verified through full-chip LMC runs. Potential uses of this technology are for process transfers from one fab to another where the OPC signature in the receiving fab is similar but not identical to the signature of the originating fab.

The tuning application is investigated with respect to its applicability in a production environment, including further metrology effort reduction by using scatterometry tools.

**Keywords:** scanner matching, LithoTuner, scatterometry, hotspot

## 1. INTRODUCTION AND METHODOLOGY

Differences in imaging behaviour between lithographic systems of the same wavelength result in variations of optical proximity effects (OPE). Scanner tuning can be used to compensate these irregularities by calculating scanner specific adjustments of the exposure conditions. The calculation is done through the determination of scanner manipulator sensitivities of relevant structures followed by an optimization to adjust the structures CD values to be close to the desired values.

Traditionally, scanner tuning methods have relied heavily on wafer-based CD metrology to characterize both the initial mismatch as well as the sensitivities of CDs to the scanner tuning knobs [1]. These methods have proven very successful in reducing the mismatch, but their deployment in manufacturing has been hampered by the metrology effort. In this paper, we explore the possibility of using ASML's LithoTuner PatternMatcher FullChip (PMFC) to reduce the dependence on wafer CD metrology by using computational lithography scanner models that maximize the use of scanner metrology and design data.

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The scanner specific models used in scanner tuning are created starting from a scanner fingerprint file of the un-tuned scanner exposure. The scanner fingerprint contains scanner specific on-tool metrology related to the exposure. A resist model calibration emphasizing enhanced sensitivity prediction is performed using FEM wafer metrology.

Offset models are then created using on-tool metrology at perturbed conditions and maintaining the resist portion of the model. These models along with the nominal condition model are used to predict the scanner sensitivities to the tuning parameters. The sensitivities are used in the linear optimization that outputs the tuning parameter offsets necessary to adjust the structures CD values to be close to the desired values. Finally, a new after tuning model is created and used to calculate the CD change induced by the tuned scanner settings.

The linear optimization in scanner tuning tries to correct the printing CD of a small set of patterns to make them closer to the expected target CD, while minimizing the impact on other patterns that are deemed to be within specifications. Additional tuning targets can come either from patterns that are important to the application, or from using full chip verification tools with the scanner model to automatically select the patterns that are most likely to become yield limiters. Furthermore, similar verification tools can be used to evaluate the impact of the actual optimized scanner settings on the full chip layout.

## 2. DESIGN HOTSPOT FIX ON A POLY 28NM LAYER

The methodology outlined in section 1 is not only suitable for tool matching and OPE tuning, but can be used to fix so-called design hotspots as well, without affecting other patterns in the same design that print on target. This application has been described previously [2] and is used as a starting point for this study.

Figure 1 shows the improvement achieved with the Design Hotspot Fix (DHF) methodology on the through pitch signature of an early development cycle Poly 28nm layer. The measured Pre-DHF signature in blue could be significantly improved to achieve the measured outcome shown in red by the tuning of NA, sigma, focus range and Pupicom spokes (see Table 2 for exact tuning recipe). Figure 6 quantifies the improvement achieved, showing that the final measured improvement for this fixing methodology is 10% when looking at the total range and even close to 50% when looking at RMS values.

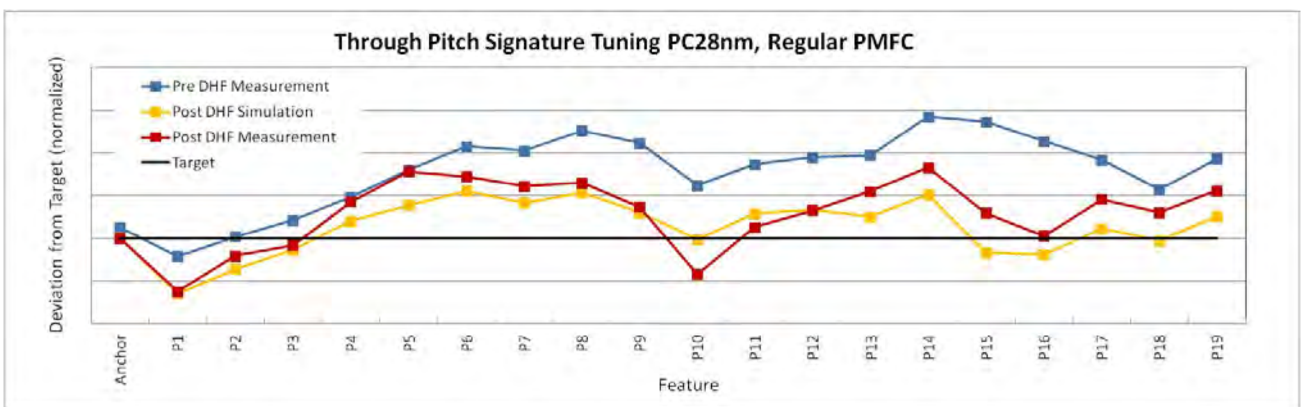


Figure 1. Design Hotspot Fix (DHF) improvement of the through pitch signature of an early development cycle Poly 28nm layer: the blue line marks the Pre DHF signature, the yellow and red line show simulation and wafer results after optimization.

## 3. POST TUNING FULL CHIP VERIFICATION

In the Design Hotspot Fix methodology it is critical to carefully choose the patterns that will be used during optimization, to make sure that the optimization will not arrive at tuning offsets that degrade the actual performance. These patterns are monitoring sites and so-called warmspots – design locations that are weak enough that they might become hotspots if the optimization is not aware of them.

As seen in Table 2, the tuning offsets required to achieve these results are quite significant. Thus, it becomes more important to make sure that the offsets do not affect the process performance. To make sure that no potential weak spots were missed during optimization, it is good practice to run a full chip Lithographic Manufacturability Check (LMC) verification through process window in order to compare contours for the processs of record (POR) parameter set and the tuned parameter set.

For this study, process-window simulations of both the POR and tuned exposure were run, and contours were compared at corresponding points in process window. Errors were flagged where the difference in contours between conditions was above a certain threshold. During a user review, sites were chosen for SEM review and verification based on significant, easy to verify differences in printing performance.

Figure 2 and Figure 3 below show exemplary results of such a verification run. We picked sites that showed significant differences in occurrence of critical printing failures (necking and bridging). All simulation results showed a reduction in the occurrence of critical failures after tuning.

Figure 2 shows one specific example where there is no significant difference in printing performance at the nominal condition, but the POR process showed significant bridging tendency at defocus and underexposure, while the same simulation indicated that the tuned process should be less sensitive. This was shown to correlate very well with the experimental results.

In Figure 3, a location was detected by LMC that already showed a pronounced bridging tendency at best point for the POR process, leading to severe bridging at underexposure. Again, the simulation predicted better performance for the tuned exposure recipe with no bridging at the nominal condition, but also a noticeable tendency to bridging features in underexposure. This also was demonstrated experimentally.

In conclusion, those results give a good indication that a model calibrated mainly to predict the process sensitivity to changes in exposure parameters can still be used to give a good prediction of design hotspots and changes in their behavior with changing exposure conditions.

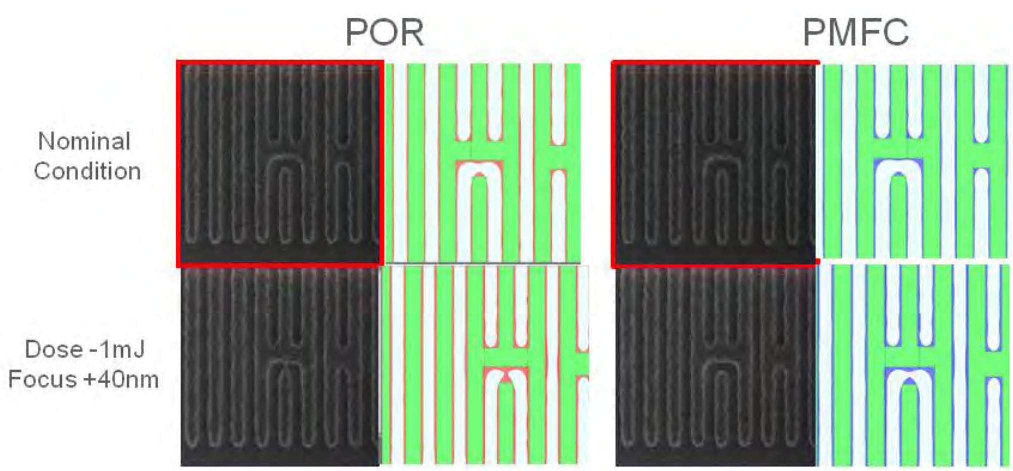


Figure 2. Simulated and measured contours of hotspots detected by an LMC run with POR settings (corresponding to the red contour) and DHF settings (corresponding to the blue contour); images at nominal condition and at one offset condition are shown.

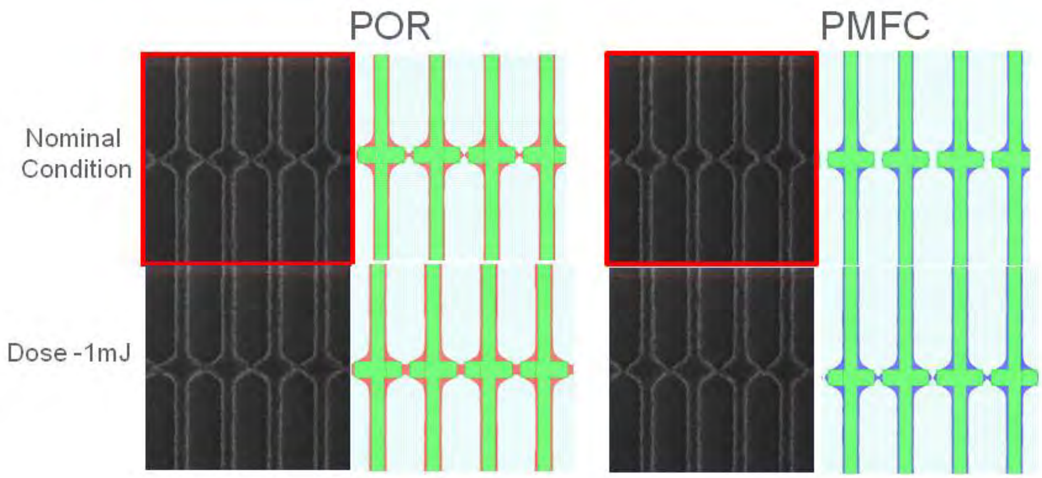


Figure 3. Further example of a bridging site for POR and PMFC settings: the difference in bridging behavior is well reproduced by simulations based on the calibrated model at POR condition and the perturbed model with PMFC settings after Design Hotspot Fix.

## 4. HOTSPOT FIXING RESULTS USING A FLEXRAY SOURCE

Regular scanner manipulators used in the PMFC tool for matching and hotspot fixing are NA, sigma, focus range and Pupicom knobs, the latter offering basic manipulations of the source energy distribution. The newly developed FlexRay extension of PMFC is able to optimize freeform illumination shapes and hence possesses more degrees of freedom for adjustment. In this section first results of a Design Hotspot Fix (DHF) based on „FlexRay only" tuning are presented and compared with those obtained using regular scanner manipulators as shown in section 2. All experiments were conducted on an ASML XT:1950i scanner with FlexRay capability.

The benefit of freeform illumination optimization is demonstrated based on the same through pitch signature tuning of an early development cycle Poly 28nm layer shown in Figure 1. The goal of the optimization is to force CD's of respective patterns to target. Originally, the illumination used in the process was a regular Quasar setting.

Depending on the target process, critical features could be constrained to one orientation, or can be allowed to occur in both x- and y-direction. This needs to be taken into account during the source optimization – if the resulting FlexRay source needs to support printing of critical features in both x- and y-direction, the optimization needs to be constrained to a higher symmetry (D4). If only one direction is allowed, the optimization can be constrained to a lower symmetry along one axis only (D2), thus giving the optimization algorithm more freedom to come up with an optimal result.

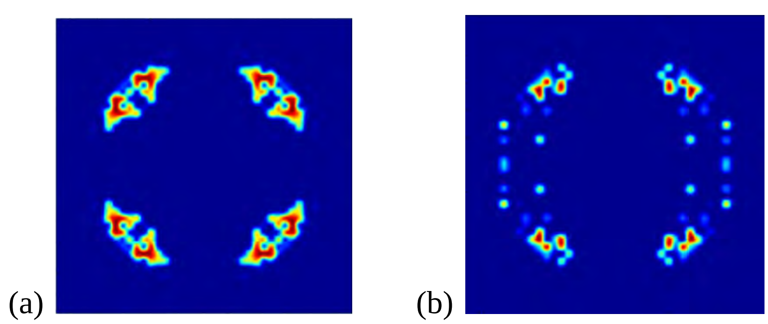


Figure 4. Freeform illumination shapes obtained for a DHF with FlexRay tuning capability: (a) optimized source by enforcing D4 symmetry, (b) source with D2 symmetry. The original source is a conventional Quasar illumination.

In Figure 4, the resulting source for both types of optimization is shown. The different symmetry constraints are clearly visible in the resulting source shape. While the source that was constrained to the D4 symmetry still looks somewhat like the original quasar setting, the optimization for the D2 symmetry constrained caused a much larger change. For the rest of this chapter, the source with the D2 symmetry will be used, since this larger change provides more interesting results.

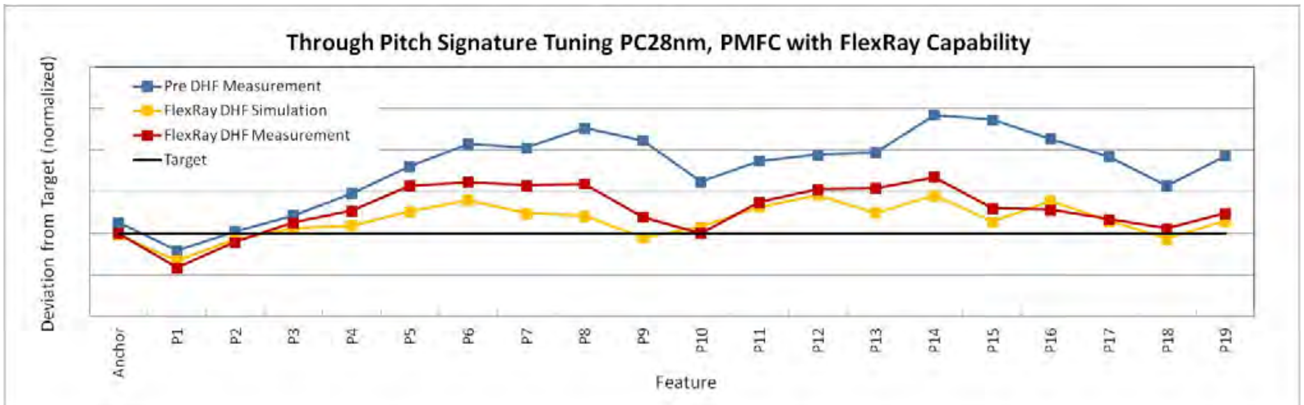


Figure 5. Through pitch improvement using a FlexRay source with D2 symmetry as shown in Fig. 4 (b); testcase as described in Fig. 1 with identical scale of normalized deviation from target. It is shown that use of a flexible source improves the RMS deviation from target compared to regular tuning.

Figure 5 shows the tuning result achieved with the D2-symmetric source. The improvement achieved by this tuning is compared in Figure 6 with the result from the regular DHF tuning. The tuning potential predicted by simulation shows an improvement of more than 50% when looking at the range of CDs after tuning and more than 70% when looking at RMS. While this could not be fully realized experimentally, the result from wafer exposure still shows significant improvement when compared both to the pre-fixing performance and the tuning result shown in section 2.

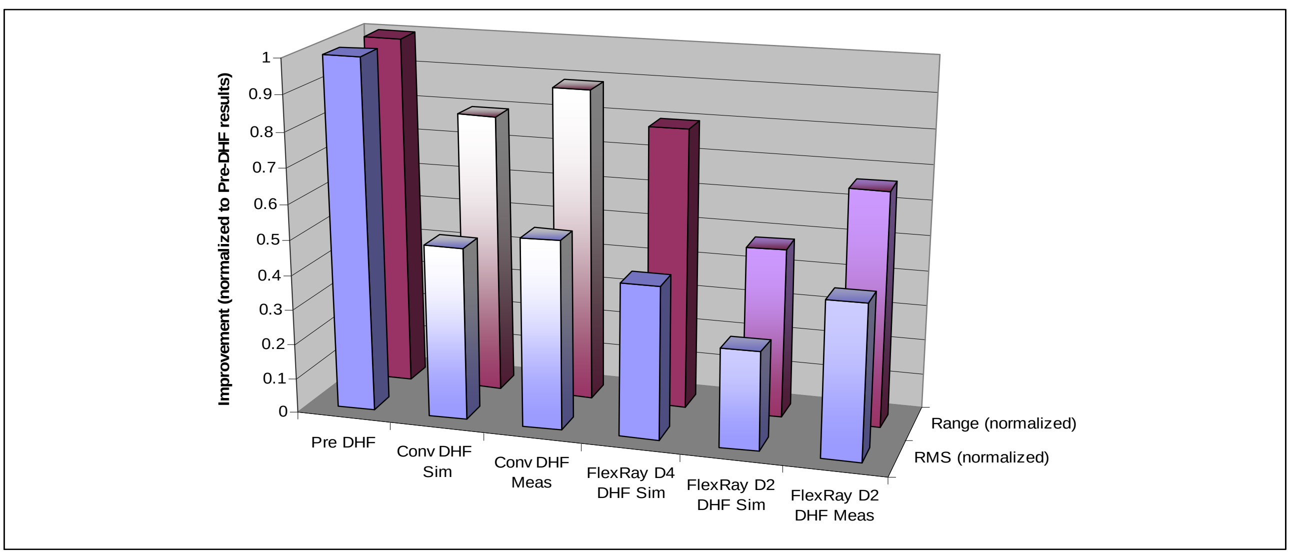


Figure 6. Normalized improvement (deviation from target, shown are Range and RMS over all pitches) for different tuning scenarios: conventional DHF based on NA, sigma, focus range and insertion of pupicom spokes compared to tuning results based on a flexible source; both simulation and wafer results are given.

A LMC full-chip run with the flexray source showed prediction results very similar to the ones shown in section 3 for the regular tuning recipe, indicating slightly improved performance through process window and at best condition when looking at the occurrence of critical failures.

## 5. REDUCING METROLOGY TIME AND EFFORT WITH SCATTEROMETRY

Modeling data was collected based on traditional SEM metrology as well as using a YieldStar scatterometry tool. The primary intention for collecting scatterometry CD data was to evaluate the use of that data for tool matching, looking for reduced data collection time for that purpose [4].

However, the models created for matching can be used for hotspot fixing without any change. Since hotspot data is usually based on SEM metrology, this provided the possibility to check fixing recipe performance and results in a situation where the underlying model is based on scatterometry data.

### 5.1 SEM and scatterometry data comparison

When comparing models, it makes sense to always have a quick look at a comparison of the underlying data.
Figure 7 shows such a comparison. For 1D-data, SEM and scatterometry measurements match very well except for a small constant offset. For 2D-data, there seems to be a lot more noise.

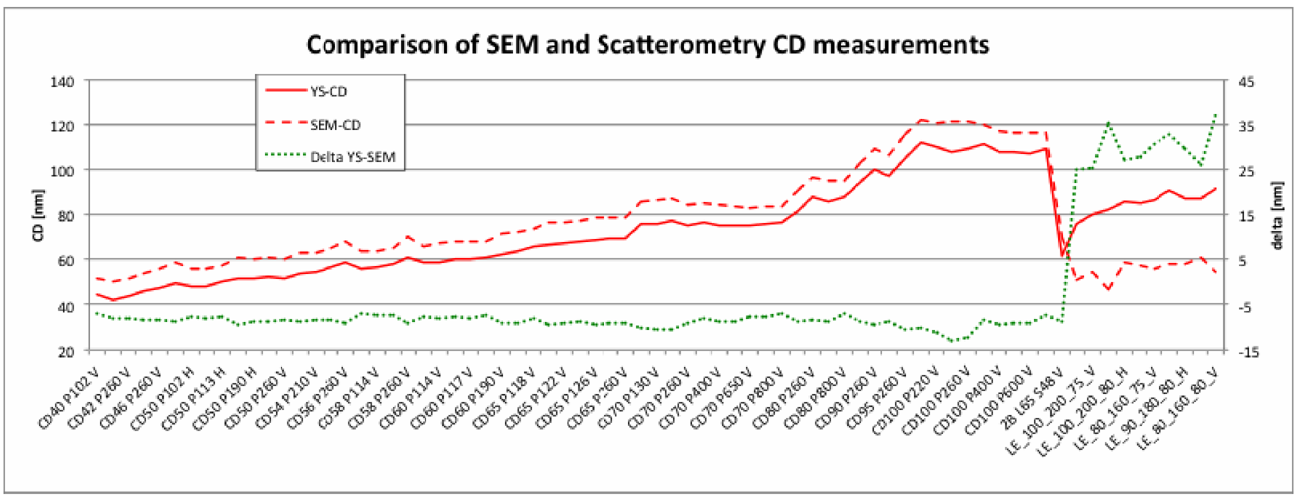


Figure 7. Plot of SEM and scatterometry measurements over feature CD. 2D features are on the right hand side of the chart.

When looking at the correlation between SEM and scatterometry data separately for 1D and 2D data (see Figure 8), it can be seen that the offset for 2D data behaves significantly different. It is not only changing sign compared to 1D data, but it also varies with feature size. This might be due to the use of different measurement algorithms on SEM and YieldStar scatterometry tool; further investigation into that effect is ongoing, but would exceed the scope of this publication.

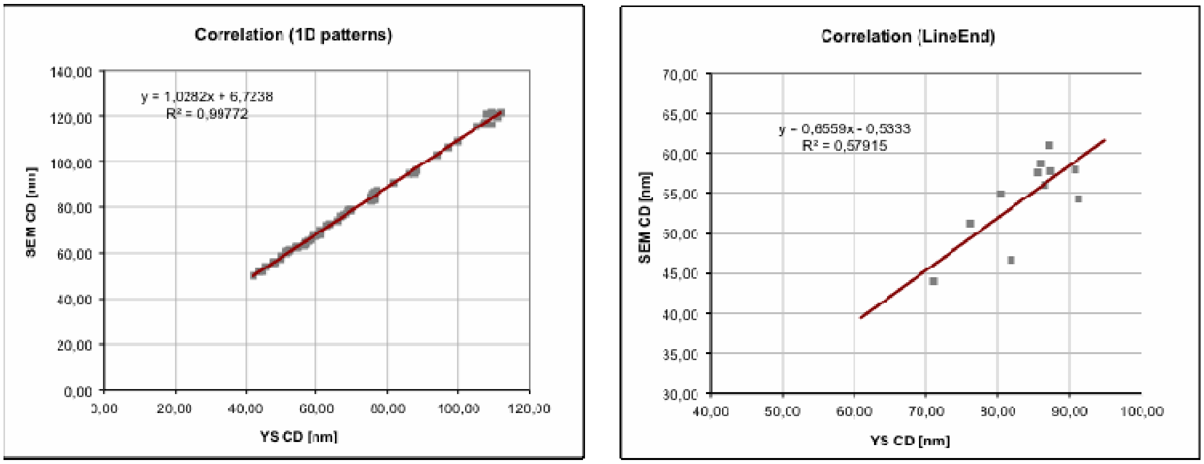


Figure 8. Correlation plot between SEM and scatterometry data. For 1D data, the slope of a linear fit is close to 1, indicating a constant offset. For 2D data, the slope is smaller than one, indicating an offset that changes with feature size.

### 5.2 Predicting CD sensitivities to tuning knobs with a scatterometry-based model

Matching of raw measurement results as discussed in the previous paragraph is an important topic with still many open questions; however, for this work the critical feature is how well the models created from that measurement data match. This is due to the fact that for fixing design hotspots by modifying scanner parameters, the matching of absolute CD prediction is of less interest. What is most important to this specific application is the correct prediction of CD sensitivity to certain tuning knobs. As an example, the sensitivities for NA and center Sigma are plotted in Figure 9. Both scatterometry-based models predict sensitivities very close to the prediction of the original SEM-based model. Additionally, there seems to be a systematic mean offset in the prediction for the scatterometry 1D model, while no systematic difference between models can be observed for the 3σ variability of the prediction.

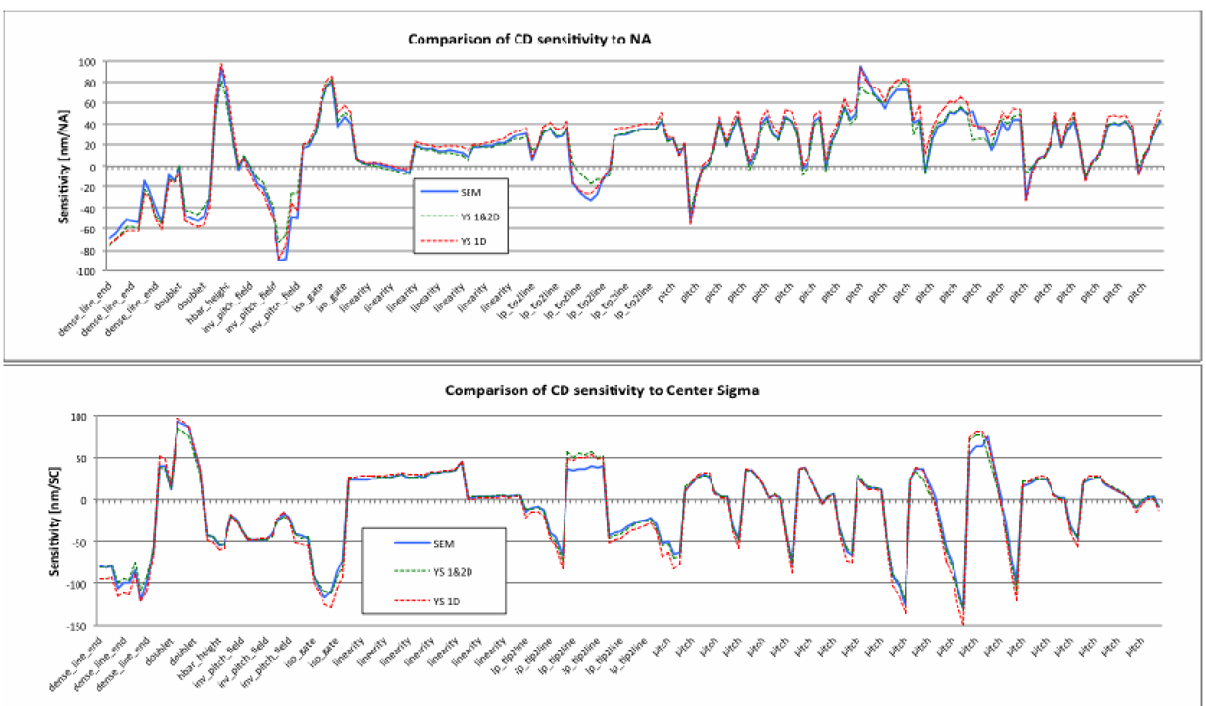


Figure 9. Sensitivity of several types of 2D and 1D features to changes in exposure tool settings, simulated with three models built respectively based on SEM data, 1D-only scatterometry data and 1D&2D scatterometry data.

| | NA | | Sigma Center | |
|---|---|---|---|---|
| | **1D** | **2D** | **1D** | **2D** |
| **Mean Δ to SEM** | 3.5 | 0.6 | -2.7 | 0.1 |
| **3σ Δ to SEM** | 16.8 | 19.9 | 22.6 | 16.2 |

Table 1. Statistical comparison of sensitivity prediction for scatterometry models compared to SEM model, based on data in Figure 9. Mean sensitivity shows a systematic offset vs SEM reference for scatterometry model based on 1D data; this disappears when including 2D data.

### 5.3 Scanner tuning using scatterometry-based models

After looking at modeling data and comparing model predictions for the important parameters, the final proof for the suitability of a model lies in the matching recipe it produces. In Section 2, the hotspot fixing results achieved with a model based on SEM metrology have been shown already.

| | Original | SEM model | 1D model | 2D model |
|---|---|---|---|---|
| NA | 1.35 | -0.04 | -0.04 | -0.04 |
| Focus Range (nm) | 0 | 200 | 201 | 200 |
| **Pupicom spoke 1** | **7.99** | **1.53** | **1.53** | **1.53** |
| **Pupicom spoke 2** | **8.48** | **1.40** | **1.40** | **1.40** |
| Pupicom spoke 3 | 8.34 | 8.16 | 8.16 | 8.16 |
| Pupicom spoke 9 | 8.34 | 8.16 | 8.16 | 8.16 |
| Pupicom spoke 10 | 8.72 | 7.78 | 7.78 | 7.78 |
| **Pupicom spoke 11** | **8.18** | **2.42** | **2.42** | **2.42** |
| **Sigma In** | **0.6** | **0.063** | **0.04** | **0.058** |
| **Sigma Out** | **0.85** | **-0.039** | **-0.027** | **-0.044** |

Table 2. Comparison of tuning offsets for conventional (non-flexRay) tuning vs original settings between reference SEM model and scatterometry models based on 1D-only data and 1D&2D data.

For the scatterometry model, exactly the same hotspot fixing runs were executed. Hotspot, warmspot and monitoring patterns were set identically. The only difference was that the SEM data based model was swapped against the scatterometry-based models. Results of that experiment are shown in Table 2, with results in bold being most meaningful for the comparison of the tuning recipes; non bold results were constrained by the limits set on the tunable range of the parameters. As can be seen, the scatterometry based models result in similar changes in the tuning parameters, with the model that used the full scatterometry dataset yielded a result closer to the original SEM model, while the scatterometry model built with 1D data only produces slightly smaller Sigma changes.

### 5.4 Suitability of scatterometry for model generation

Looking back at the raw measurement data, significant differences between data collected by SEM metrology and data collected with a scatterometry tool have been found, especially for 2D features.

When evaluating model predictions, in this case the sensitivity predictions used for the hotspot fixing application, it seems that those differences do not matter too much for generating results that are equivalent to the ones from an SEM based model. Moreover, the scatterometry based model including the 2D data shows indications of being closer to the mean sensitivity given by the SEM model.

The final proof of this is found when looking at hotspot fixing recipes, where the recipe generated when the model includes the 2D scatterometry data is virtually identical to the one generated by the SEM based model. The 1D-model still gives results close to those achieved with the SEM model, but has slightly larger differences in suggested Sigma settings. This indicates that having 2D data available for sensitivity determination is important, while the absolute correlation of this data between scatterometry and SEM measurements is secondary.

## 6. CONCLUSION AND OUTLOOK

The PMFC methodology for simulation-based scanner matching was demonstrated in previous publications already. This work was intended to provide pieces that are missing for using the method in a production environment. Specifically, we demonstrated the following capabilities:

- First, we showed that LMC simulations through process window using the post-tuning models are not only capable of predicting locations of large change in printed contours, but match the wafer results for critical failure locations very well. This means that full-chip LMC can be used to qualify tuning recipes for production use.
- Second, using a FlexRay source instead of tuning of conventional scanner parameters like NA and Sigma provided more degrees of freedom, resulting in further improvements in tuning results.
- Finally, it was shown that scatterometry-based models can be used for tuning, thus reducing the load on CD-SEM metrology tools and enabling faster data collection for model building. It was shown that having 2D information from scatterometry available for model-building generates tuning recipes very close to the reference recipe based on SEM data.

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